CHARACTERIZATION OF PASCHEN CURVE ANOMOLIES AT HIGH P*D VALUES

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Abstract

Paschen's law is often used to estimate the breakdown voltage of high pressure gas switches commonly used in high voltage pulsed power systems based on the product of pressure and distance (pd) in a given gas. Paschen's law predicts breakdown voltages for high pd values that scale approximately linearly with pd. However, it is clear from published literature and ARC Technology's experimental data that the breakdown voltage deviates significantly from the theoretical Paschen curve at relatively high pd product values. It is also clear that these results are not consistent for different gap spacings and pressures with the same pd product. Therefore, initial tests have been performed to characterize this region of the paschen curve for N2, H2, and SF6 for pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm.

I. INTRODUCTION

A. Background to Paschen's law

Friedrich Paschen studied the breakdown voltage of parallel plates in a gas. In 1889 he stated what became known as Paschen's law which describes the relationship between breakdown voltage, and the product of pressure and distance for a parallel plate geometry for a given gas composition [1]. Paschen's law can be written as Eq. (1), where a and b are constants dependent on gas composition. A plot of this equation produces a characteristic shape known as the Paschen curve, which is shown in Fig. 1 for air in a log-log plot.

$$V = \frac{a(pd)}{\ln(pd)+b} \tag{1}$$

Significant research has been conducted over many years to determine the physical mechanisms that dominate the gas breakdown process. A good reference on the subject is [2], which describes in detail the Townsend discharge theory and the streamer theory.

B. Applications of Paschen's law.

Observations of the Paschen curve show three distinct regions of operation for a system operating in a gaseous environment. High voltage hold-off is achieved by operating in either the low or the high pd region, which are often referenced as operating on the left-hand or right-hand side of the Paschen cure. The third region is the area around the Paschen minimum.

High voltage pulsed power systems often employ gas switches due to their high power and voltage handling capabilities. Vacuum switches such as the thyratrons operate on the left-hand side of the Paschen curve. Pressurized spark gaps operate on the right-hand side of the Paschen curve. Both of them stay away from the middle region to maximize voltage hold-off.

Microelectromechanical systems (MEMS), on the other hand, are typically concerned with the middle region of the Paschen curve for design safety. The Paschen minimum is applied to designing systems that will never experience voltage breakdown with any gap spacing for a given pressure, provided that it is operated below a maximum threshold voltage.

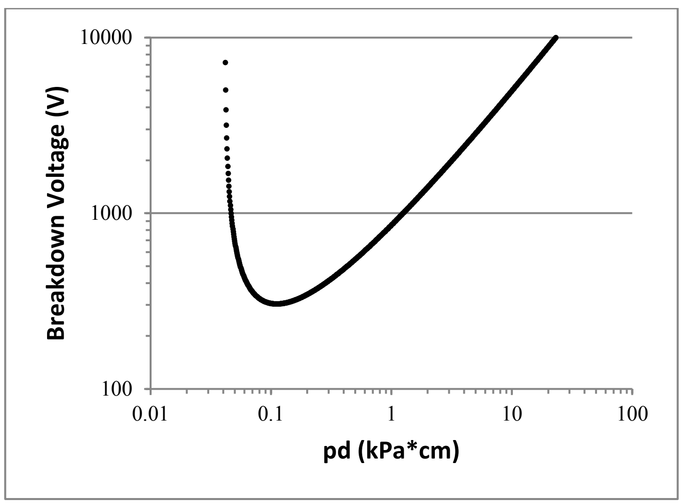

Figure 1. Paschen curve for air.

C. Limitations of Paschen's law

The limitations of Paschen's law for the micron gaps commonly employed in MEMS is well-documented, and has lead to the development of the "modified Paschen curve"[3]. These limitations normally affect devices with gaps in the low

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14. ABSTRACT

Paschens law is often used to estimate the breakdown voltage of high pressure gas switches commonly used in high voltage pulsed power systems based on the product of pressure and distance (pd) in a given gas. Paschens law predicts breakdown voltages for high pd values that scale approximately linearly with pd. However, it is clear from published literature and ARC Technologys experimental data that the breakdown voltage deviates significantly from the theoretical Paschen curve at relatively high pd product values. It is also clear that these results are not consistent for different gap spacings and pressures with the same pd product. Therefore, initial tests have been performed to characterize this region of the paschen curve for N2, H2, and SF6 for pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm.

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micron range operating at atmospheric pressure and are attributed to field emission.

Similar departures from Paschen's law are observed with spark gaps in the millimeter and centimeter range when operating at higher pd values. Preliminary tests to characterize these limitations at higher pressures have been performed and presented in this paper.

II. EXPERIMENTAL SETUP

The experimental setup, shown in Figure 2, was designed to automate the tests as much as possible to obtain consistent results. A 125kV Glassman power supply was set to ramp from zero to maximum voltage in 120 seconds by driving its external control with a reference voltage from a function generator. The high voltage output of Glassman power supply was connected to a pair of 2.54cm spherical stainless steel electrodes in a G10 pressure chamber capable of 2000psi. The voltage monitor output of the high voltage power supply was measured by a Tektronix TDS6154C oscilloscope, which can capture data prior to triggering by recording a continuous window and then freezing when triggered. An antenna located near the electrodes detected the breakdown event and triggered the oscilloscope which then recorded the voltage just prior to breakdown.

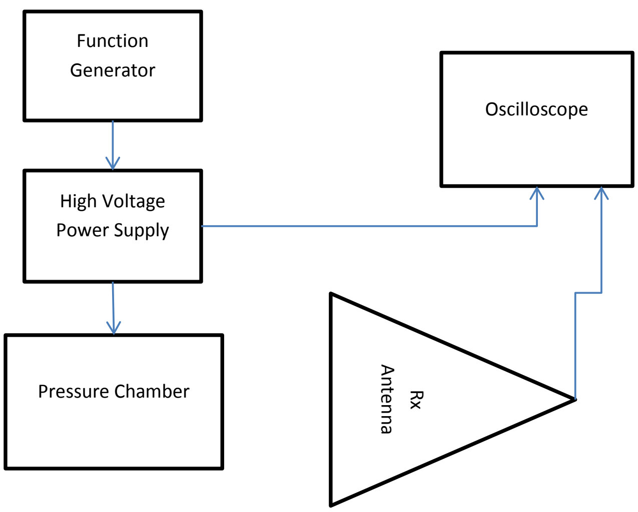

Figure 2. Block diagram of test setup for determining breakdown voltage.

III. RESULTS AND DISCUSSION

A. Test parameters

The Paschen curve breakdown characteristics were measured for N_2, H_2, and N_2 with 10% SF_6 at pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm. The test was replicated ten times at each parameter setting to determine the average breakdown voltage and standard deviation.

B. Experimental Paschen Curve Testing

Test results for a typical data set are shown in Fig. 3, which is measured with N_2 at 1.27mm. The initial steep slope is consistent with the Paschen curve (green line). However, a departure occurs at approximately 1400kPa where the slope decreases. This change is accompanied by an increased standard deviation in the data for tests within the same set, which is represented in Fig. 4. This general pattern occurred for all gases and spacings, with the point of departure from the theoretical Paschen curve changing based on the specific gas and spacing.

The ten sample data set is adequate for the linear region where the standard deviation is low. However, it is noted that the regions of high standard deviation require many more data points for statistical accuracy, which explains the widely varying data in Fig. 4 above 200 kPa*cm. However, the focus of the paper is to investigate the point of departure from Paschen theory. Since the high standard deviation data clearly shows the general trends it is included in the plots.

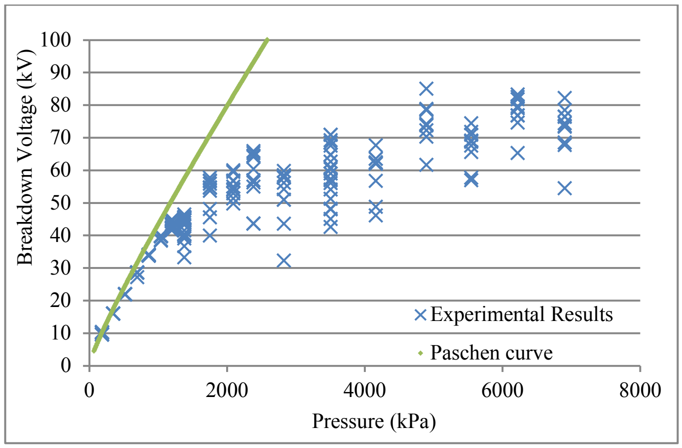

Figure 3. Test results with N2 and electrode spacing fixed at 1.27mm.

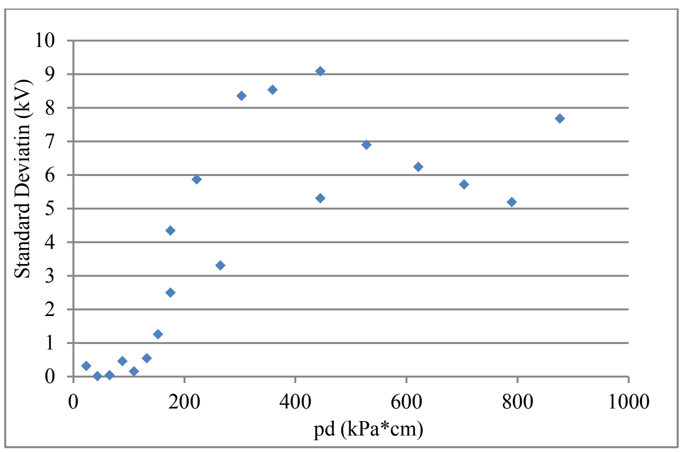

Figure 4. Standard deviation of the 1.27mm N_2 gap

The average breakdown voltages versus pd were measured for each gas over the designated parameter space and are summarized in Fig. 5, Fig. 6, and Fig. 7. The figures are

plotted linearly, rather than with log scales, to more easily interpret the data visually. It is important to note that for high pd values the theoretical Paschen curve is linear. The data tracks this line for lower pd values, which is especially evident below 100kPa*cm. Each set of data ultimately changes slope, which indicates a departure from the theoretical Paschen curve. Unfortunately, the power supply limit of 125kV prevented the characterization of the SF_6 -N_2 mixture at the higher pd values of the other gases.

Larger gap spacings enable the spark gap to maintain conformance with the theoretical model to higher pd values, which is consistent with published literature from many references. The point divergence of the measured data from theoretical for N_2 and H_2 at the 2.54 mm gap spacing is consistent with an interpolation of the results published by [4], but no comparable results were presented for the 0.508mm and 1.27mm gap spacings. In fact, the Paschen predictions have been verified to be accurate for a spark gap filled with SF_6 with a 1.8cm spacing operating at 1,600kPa*cm [5]. Therefore, the departure from theoretical cannot be predicted simply based on a threshold pd product.

Analysis of the higher pd data suggests that in some cases the breakdown voltage begins to plateau for a given gap spacing while the pressure continues to increase. This would be an expected result of field emission at high electric fields, which is a known factor that can influence voltage breakdown characteristics. However, this characteristic is not consistent for all data sets. In fact, Figs. 6 and 7 show 3 data sets that indicate not only a plateau, but also a decrease in breakdown voltage with increased pd. This is not an expected result of field emission and indicates that another factor is influencing the performance. Clearly, much more data would be required to characterize this portion of the Paschen curve.

C. Electric field calculations

The maximum electric field strength **Em** is calculated by Eqn. (2), where **Vbd** is the average breakdown voltage, **d** is the respective gap distance, and **f** is the field enhancement factor for the given spark gap geometry. The calculation of **f** for two spherical spark gaps with a radius **r** that are separated by a distance **d** is shown in Eqn. (3). The field enhancement factor is nearly unity for the dimensions in this series of tests.

$$\mathrm{Em} = \frac{\mathrm{f(Vbd)}}{\mathrm{d}} \quad (2)$$

$$\mathrm{f} = \frac{0.9(\mathrm{r}+\frac{\mathrm{d}}{2})}{\mathrm{r}} \quad (3)$$

The electric field breakdown for the three gasses is plotted in Fig. 8, Fig. 9, and Fig. 10 with respect to pressure. It is important to note that the electric field at breakdown is very similar for all three gap spacings until the 25 to 35kV/mm region is achieved. Beyond this point, the smaller gap spacing actually provides a greater field strength. Further study is required to understand the reason for this effect.

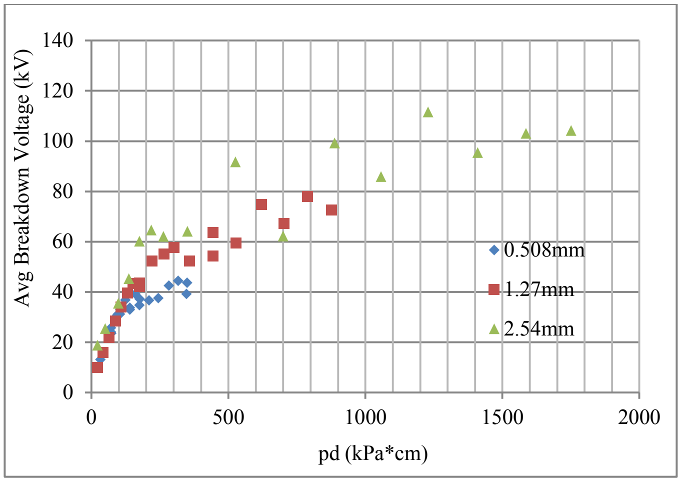

Figure 5. Breakdown voltage compared to pd for N_2.

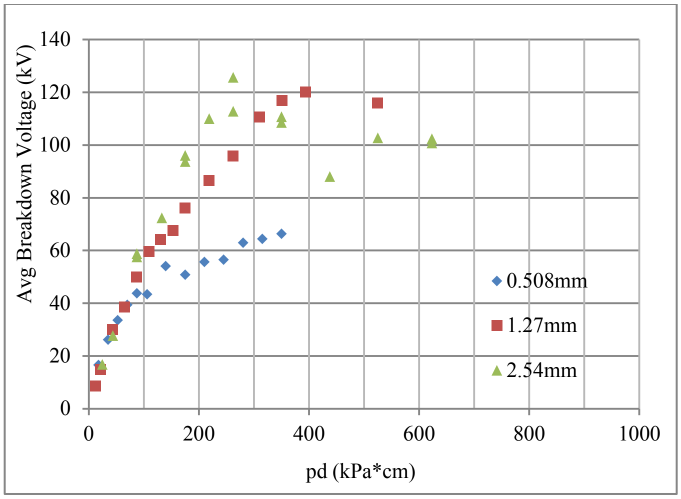

Figure 6. Breakdown voltage compared to pd for 10% SF_6.

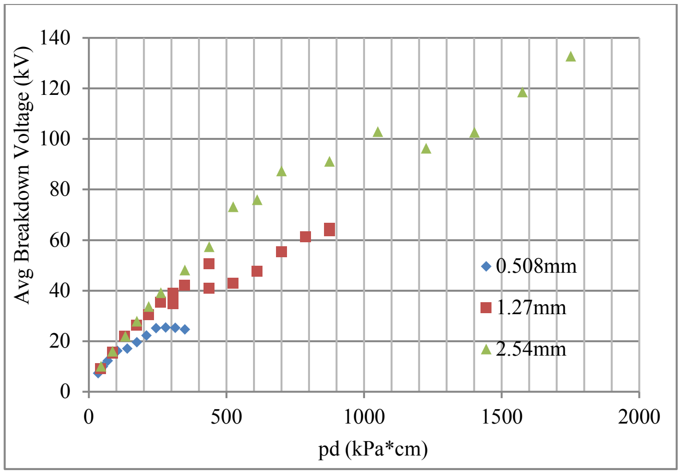

Figure 7. Breakdown voltage compared to pd for H_2.

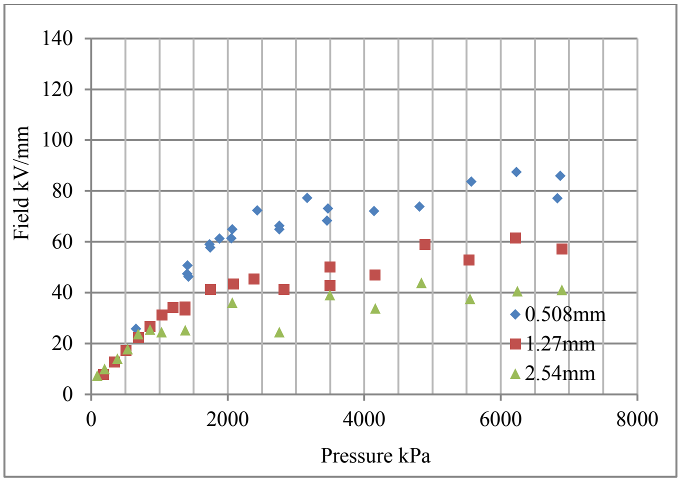

Figure 8. Electric field compared to pressure for N_2.

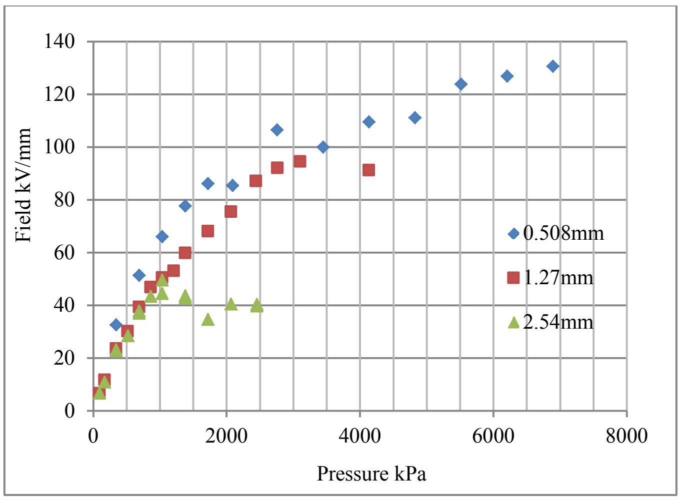

Figure 9. Electric field compared to pressure for 10% SF_6.

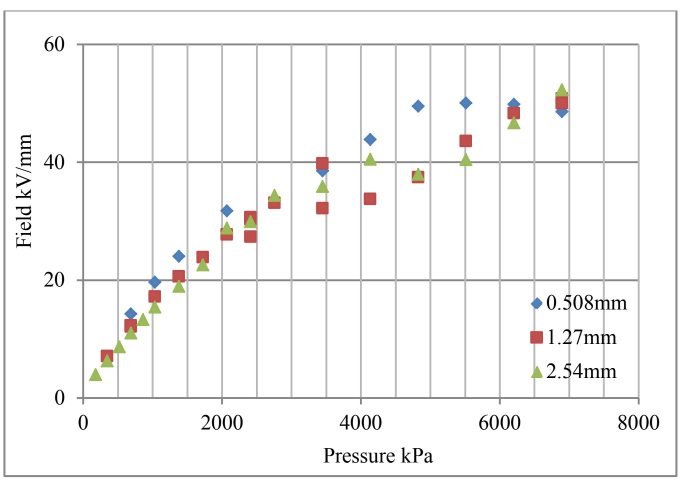

Figure 10. Electric field compared to pressure for H_2.

IV. CONCLUSIONS

Experimental testing has quantified the breakdown voltage versus pd for N_2, H_2, and N_2 with 10% SF_6 at pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm. The following observations are made with respect to that data.

1. For a given spark gap geometry and spacing, increasing the pressure above a maximum level results in voltage breakdown behavior that deviates from Paschen's Law.

2. This non-Paschen region is characterized by both a reduced voltage breakdown from the predicted level and a high standard deviation between measurements at the same parameters.

3. The beginning of the non-Paschen region cannot be predicted simply by a threshold pd level.

4. Larger gap spacings maintain their conformity to Paschen's Law at higher pd values.

5. The beginning of the non-Paschen region cannot be predicted simply by a threshold electric field.

6. Smaller gap spacings permit higher electric field strengths.

This work directly applies to the design of high voltage spark gap switches. First, it may be possible to find published literature for designing a spark gap with the same gas and similar operating voltages. If not, the correct operating point will need to be determined empirically. Second, if the spark gap is smooth and clean but fires at a range of voltages, it may need to have a wider gap spacing with less pressure to stabilize for a given operating voltage

Future work is necessary to more accurately quantify the data regions that diverge from the theoretical Paschen values due to their high standard deviations.

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